DETECTOR-BASED INTEGRATING SPHERE PHOTOMETRY

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ABSTRACT

A new total luminous flux calibration facility using a 2.5 m integrating sphere has been developed at NIST. The Absolute Integrating-Sphere Method, developed for realization of the lumen in 1995, has been applied to routine calibration measurements of total luminous flux. The measurement of an external source is automated so that the responsivity of the sphere is calibrated every time a test lamp is measured. The new method based on illuminance measurement of the external source using standard photometers allows for calibration of test lamps with no need for luminous flux standard lamps. This brings the luminous flux calibration into detector-based measurement procedures, thereby eliminating the uncertainties associated with the use of working standard lamps. Lower uncertainties are achieved by shortening the calibration chain. Furthermore, a technique employing a chopper and a lock-in amplifier has been introduced to the external source, which allows for calibration of the sphere while the internal lamp is burning in the sphere to evaluate the errors due to the effect of heat on the sphere and other nonlinearities.

1. Introduction

Integrating sphere photometry allows fast measurements of total luminous flux and is widely used for measurements of various light sources. However, the use of integrating spheres has been limited to relative measurements based on the substitution method relying on standard lamps. In the substitution method, test lamps should be similar to the standard lamps in physical size, shape, spectral distributions, and intensity distributions [1,2]. If these requirements are not met, corrections must be applied, but there were no correction techniques available for the errors associated with the angular intensity distributions of lamps, which has limited the use of integrating spheres for high-accuracy applications.

A new method for an absolute measurement of total luminous flux using an integrating sphere (Absolute Integrating Sphere (AIS) method) was first proposed in 1994 [3]. With this method, the total luminous flux of a lamp inside the sphere is calibrated against the known amount of flux introduced into the sphere from an external source through a calibrated aperture, with a correction to account for the spatial nonuniformity of the sphere responsivity over the sphere wall. Experimental evaluations of this method were reported with successful results [4, 5]. The luminous flux unit was officially realized using this method by NIST in 1995 [6]. This method, however, was available only for the realization of the unit due to limitations of the facility, and routine calibrations of total luminous flux have been still based on the substitution method.

The AIS method has now been applied to routine total luminous flux measurements at NIST using a newly developed 2.5 m integrating sphere [7]. This facility enables absolute measurements of test lamps with no need for luminous flux standard lamps. Calibrations are based on the illuminance measurement of an external source with standard photometers, thereby introducing a detector-based procedure for the total luminous flux calibration. A higher accuracy is achieved as the calibration chain is shortened with the standard lamps and the transfer process eliminated. This method also provides an advantage of automatically correcting for the self-absorption of the test lamps and the drift of the sphere responsivity during the measurement session. The process of the realization of the lumen and subsequent recalibration of many working standard lamps are no longer necessary. Instead, the standard photometers are to be calibrated periodically to maintain the unit.

Furthermore, a technique employing a chopper and a lock-in amplifier has been introduced to the external source, which allows for calibration of the sphere while the internal lamp is burning. This is a similar technique known for detector linearity measurements [8]. Possible changes of the sphere responsivity (e.g., due to the effect of heat from the lamp when the internal lamp is turned on) can be evaluated as well as any nonlinearity of the photometer. The principles and characteristics of the new NIST integrating sphere facility along with its uncertainty budget are reported.

2. Measurement facility

Figure 1 shows the geometry of the NIST 2.5 m integrating sphere. The sphere is coated with a barium-sulfate-based coating having a reflectance of approximately 98 % in the visible region. The high-reflectance coating was selected for better spatial uniformity of the sphere responsivity. The baffle surfaces are coated with the same coating. The sphere basically consists of a photometer head, two baffles, an external source system, and a lamp holder, arranged in a similar design as in previous work [6]. Baffle 1 (20 cm in diameter) is normally located at 62 cm from the photometer head, but its position is movable. Baffle 2 (15 cm in diameter) is placed as close to the opening as possible (28 cm from the opening) while not intercepting the external beam. The lamp holder can be mounted from the top or the bottom of the sphere to allow base-up or base-down operation of the lamp. A four-pole screw-base socket or other special socket including one for 4-foot (121.92 cm) linear fluorescent lamps is attached to the lamp holder.

The external source system employs an aperture/photometer wheel at the sphere opening, which is computer-controlled and has four positions. A precision aperture (40 mm or 50 mm in diameter) is mounted in one position, and a black mask in another position that works as a shutter to block the incoming beam. The wheel is placed as close to the sphere opening as possible to minimize diffraction losses. The other two positions are used to mount the standard photometers to measure the illuminance at the center of the aperture. These standard photometers are aligned so that their reference planes coincide exactly with that of the aperture (within ± 0.5 mm). The photometers are temperature-controlled, known to have a long-term stability of better than 0.1 % per year, and are annually calibrated against the NIST illuminance
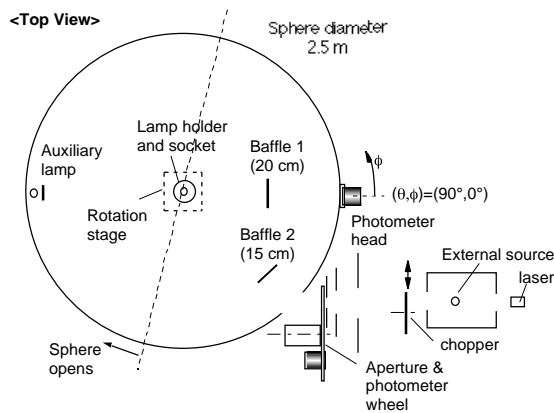
unit. A frosted-bulb, 1000 W FEL-type lamp, operated at 2856 K, is used as a light source, placed at 1 m from the aperture. A diode laser is used to align the orientation of the lamp to reproduce the illuminance distribution. The illuminance at the aperture is about 1100 lx, and the introduced luminous flux is approximately 2 lm. The sphere photometer signal for this external flux has a typical RMS noise level of 0.02 %.

The photometer for the integrating sphere is a temperature-monitored type of the same design as one used in the realization of the candela [9] but equipped with a surface-ground opal glass for cosine response. The photometer head is mounted so that the opal surface is flush with the sphere-coating surface. The photometer response together with its built-in amplifier has been verified to be linear to within 0.03 % up to 10^{-4} A of its output current, using the beam conjoiner [10]. The linearity has also been verified using the AC/DC technique, as described in the later section.

3. Characterization of the integrating sphere

3.1 Spatial response distribution function (SRDF)

The SRDF is the spatial distribution of the relative sphere responsivity over the sphere wall including baffle surfaces, and is measured by scanning a narrow beam in the sphere. The integrating sphere is equipped with computer-controlled rotation stages on the top and the bottom of the sphere, which can rotate the lamp holder horizontally. Then, at the lamp socket, another small rotation stage is mounted and rotates the beam source vertically. Thus, the beam is scanned over the 4 solid angle. The beam source consists of a vacuum miniature lamp and a lens as shown in Fig. 2. A vacuum lamp is used to make the source insensitive to its burning position (gas-filled lamps are burning-position sensitive). To verify the stability of the source in different burning positions, the beam source was firmly mounted on a small integrating sphere (15 cm diameter), and the sphere's photometer

Figure 1. Arrangement of the new NIST 2.5 m integrating sphere for the detector-based total luminous flux calibration.
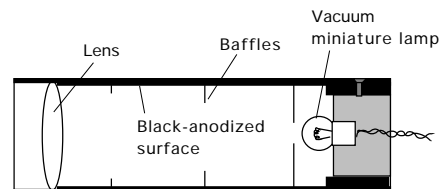

Figure 2. Construction of the beam source for the sphere scanner.

signal was measured as the sphere was rotated 360° vertically. The change of the signal was less than 0.03 %. The lens was used to keep the flux level as high as possible while minimizing the flux leaking outside the beam angle (approximately 5° – adjustable) while keeping the flux level as high as possible. The total luminous flux of the beam is approximately 0.1 lm, with 97 % of the flux within the beam angle. The SRDF of the integrating sphere was measured at 5° intervals for both the azimuth angle (ϕ) and elevation angle (θ), and plotted as a three dimensional chart in Fig. 3. The area of $\pm$ 5° around the hot spot (the area where the external beam hits) was further mapped at 1° intervals (not shown) to determine the sphere responsivity for the hot spot that has approximately twice the spot size of the beam source. Prior to each vertical scan, the beam position was moved to a reference point so that the stability of the beam source could be monitored and corrections applied for the drift of the lamp during the scan. In Fig. 3, $\theta = 0°$ at the top and $\theta = 180$ ° at the bottom of the sphere, and ϕ =0°,360° is the plane where the photometer head is located. Various structures in the sphere are seen in the data: the effect of Baffle 1 at (θ, ϕ)=(90°, 0°) and (90°, 360°), the shadow of Baffle 1 and the lamp post at ϕ =180°, and the hemisphere joints (grooves at ϕ=70° and 250°). It is also observed that the responses in the upper hemisphere appear slightly lower than in the lower hemisphere. The overall uniformity of this integrating sphere, however, is considered excellent. From the SRDF data, the spatial nonuniformity correction factors (see Ref. [6] for equations) for the external beam, scf_e, was determined to be 0.9992. The change of the scf_e over one year (Dec. 98 - Oct. 97) was less than

0.001. The correction factors for the internal source, scf_i, for several types of flux standard lamps were determined to be 0.9995 to 1.0002. The variation of scf_i due to horizontal rotation of these lamps was calculated to be within $\pm$ 0.0002.

3.2 Other characterizations of the integrating sphere

The illuminance from the external source over the aperture is not perfectly uniform, and a correction is necessary to obtain the average illuminance over the aperture from the illuminance at the aperture center. The illuminance distribution over a 50 mm x 50 mm area was measured at 1 m from the external source by spatially scanning an illuminance-meter head having an acceptance area of 3 mm in diameter. The ratio of the average illuminance E_a to the center illuminance E_c, referred to as the average illuminance factor k_a, was determined to be 0.9991 for the external source setup described above. Once k_a is determined, only E_c needs to be measured to obtain E_a.

The SRDF is defined for light incident normal to the sphere wall, while the light from the external source is incident at approximately 40°. The diffuse reflectance of the sphere coating changes with the incident angle, and the sphere responsivity for the external source is affected. The incident angle dependence correction factor k_b was measured by using the beam source (the one used for the measurement of SRDF). While aiming at the hot spot, the beam source position was moved from the sphere center to the axis of the external beam, and the ratio of the signals was
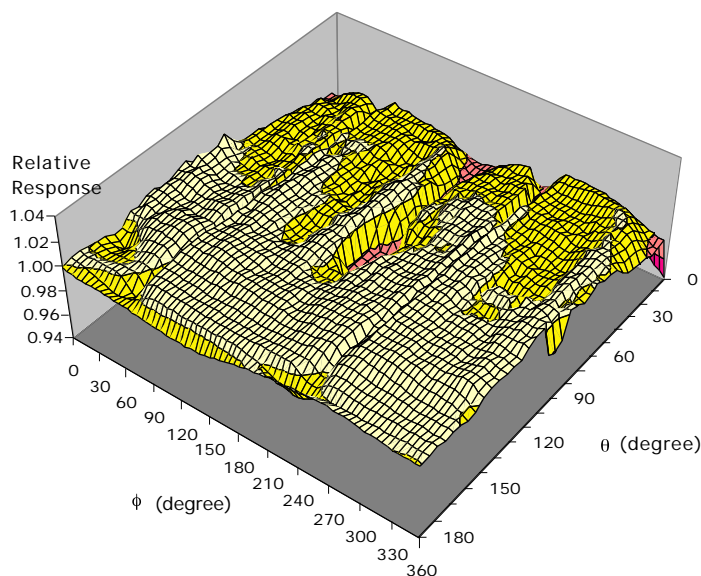

Figure 3. The mapping of the NIST 2.5 m integrating sphere responsivity (normalized SRDF).

3

taken. A correction was made for the change of the self-absorption due to the movement of the beam source. The correction factor k_b was determined to be 0.9993.

The spectral throughput of the integrating sphere and the relative spectral responsivity of the photometer head have been measured, and the spectral mismatch correction factors ccf^* (See Ref.[6]) are calculated from the relative spectral power distributions of test lamps. The correction factors are fitted to $ccf^*(T_d)$ as a function of the temperature of a Planckian source to be applied to incandescent lamps of known distribution temperatures.

3.3 AC/DC technique

The flux level of typical test lamps (10^2 lm to 10^4 lm) and that of the external beam differ by a few orders of magnitude. The measurement results are therefore susceptible to errors due to the effect of heat (by the test lamp) on the sphere and/or to the nonlinearity of the detector system. A technique (referred to as the AC/DC technique) has been developed to measure the integrating sphere characteristics while the test lamp is burning inside. A chopper is inserted in the beam path of the external source, and the introduced light is chopped at 90 Hz. When the internal lamp is turned on in the sphere, the AC signal from the chopped external beam is superimposed on the DC signal from the internal lamp. As the AC signal is very small (typically 10^{-3} of the DC signal), a lock-in amplifier is used to separate and measure the AC signal with a sufficient signal-to-noise ratio. The AC signal is monitored simultaneously with the DC signal when the internal lamp is on and off. Any change of the AC signal when turning on the internal lamp indicates a change of the sphere responsivity. The cause of the change can be thermal effects by the internal lamp on the sphere coating and/or on the photometer head (which appear as gradual changes), the nonlinearity of the photometer head (which appear as sudden changes), and/or the change of the self-absorption of the internal lamp (which is not well known). Figure 4 shows the result of the AC/DC measurement of the NIST integrating sphere with a 1000 W tungsten halogen lamp (25000 lm) operated inside. Although the noise of the AC signal is high when the internal lamp is on, the average level of the signal stays nearly constant. No obvious sudden change of the AC signal is observed, which verifies the linearity of the photometer head. A slight gradual change (0.02 % to 0.03 %) is observed, which is negligible in most cases. This technique can also be used to measure the change of the self-absorption of a discharge lamp when it is burning, which was not possible
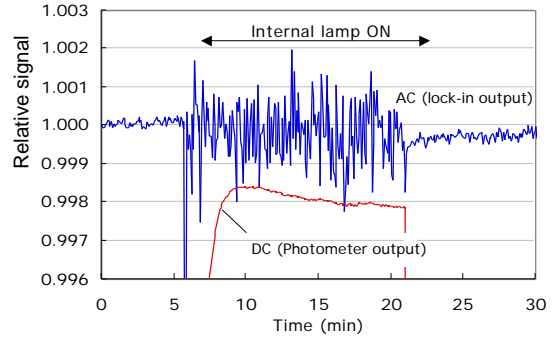

Figure 4. The result of the AC/DC measurement of the NIST integrating sphere with a 1000 W tungsten lamp operated in the sphere.

before. This technique was first introduced when Ohno conducted an experiment on the realization of the lumen at Bureau International des Poids et Mesures (BIPM), Sevres, France. The details of this study will be published elsewhere.

4. Measurement procedures

The measurement procedures using the detector-based total luminous flux calibration facility are as follows. Prior to measurement, the external source is stabilized long enough (at least 30 min) to achieve the lamp's best stability, and is operated throughout a measurement session.

(1) A test lamp (an internal source) is first measured while the external beam is blocked. The lamp is mounted on the sphere center, operated and stabilized, and the sphere photometer signal, y_{test}, is taken.

(2) With the test lamp turned off, the dark signal, y_{dark1}, is taken.

(3) While the test lamp is still in the closed sphere, the aperture/photometer wheel is set to the aperture position to introduce the external beam, and the sphere photometer signal, y_{ext}, is taken. The photometer gain needs to be changed at this time because the signal level for the external beam is normally a few orders of magnitude lower.

(4) With the external beam blocked, the dark signal (at the changed range), y_{dark2}, is taken. The dark signal must be measured again because the photometer range has changed.

(5) The aperture/photometer wheel is set to the standard photometers, and the illuminance E_c on the aperture center is measured.

4

The measurement for the test lamp is complete. The sphere responsivity, R_s (given in A/lm or V/lm), for an isotropic point source is given by,

$$R_s = (y_{ext} - y_{dark2}) \cdot ccf_e^* \cdot scf_e \cdot k_b / (E_c \cdot k_a \cdot A), \quad (1)$$

where ccf_e^* is the spectral mismatch correction factor, scf_e is the spatial nonuniformity correction factor for the external source, k_b is the incident angle dependence correction factor, k_a is the average illuminance factor, and A is the area of the aperture. The total luminous flux of the test lamp, Φ_{test}, is given by,

$$\Phi_{test} = (y_{test} - y_{dark1}) \cdot ccf_i^* \cdot scf_i / R_s, \quad (2)$$

where ccf_i^* is the spectral mismatch correction factor, and scf_i is the spatial nonuniformity correction factor for the test lamp. The correction with scf_i can be ignored for typical flux standard lamps with the NIST integrating sphere [7].

In this manner, the sphere is calibrated immediately after each test lamp is measured, thus taking into account such factors as the self-absorption of the test lamp, drift of the sphere responsivity, and sphere responsivity variations due to mechanical reproduction of the sphere closure. The total luminous flux of the lamp is then calibrated avoiding errors due to these factors.

5. Uncertainty budget

Table 1 shows the uncertainty budget for the detector-based total luminous flux measurement at NIST. To maintain the luminous flux unit, the two standard photometers (for illuminance measurement of external source) are calibrated for illuminance responsivity annually against a group of the eight NIST reference photometers [11]. The spatial nonuniformity correction factor scf_e for the external source is recalibrated biannually. Standard lamps are no longer used to maintain the luminous flux unit, though one or two monitor lamps are measured with test lamps for quality control purposes in calibration work. The overall uncertainty of the calibration of typical incandescent standard lamps is estimated to be 0.50 % (k=2), which is a notable improvement over the previous NIST calibration procedures based on the substitution method (0.74 %) [11].

6. Conclusions

The Absolute Integrating Sphere method has been applied to the new NIST 2.5 m integrating sphere for routine calibration of total luminous flux of lamps. The external source system is automated so that the sphere responsivity is calibrated every time a test lamp is measured. The new facility has made possible the calibration

Table 1. Uncertainty Budget for the NIST Detector-Based Luminous Flux Calibration.

Factor	Expanded uncertainty (k =2) [%]	
	Type A	Type B
Uncertainty of the determination of the external beam flux		
The NIST Illuminance unit realization		0.39
Transfer to the standard photometers	0.05	
Long-term drift of the standard photometers (1 year)		0.15
Photometer reference plane (0.5 mm in 1 m)		0.10
Aperture area A		0.10
Average illuminance factor k_a		0.03
Stray light in illuminance measurement		0.05
Drift of the external source during calibration		0.03
Random noise of the signal in measurement of E_c	0.05	
Uncertainty of the lamp luminous flux with respect to the external beam flux		
Determination of the correction factor scf_e		0.10
Longterm drift of the correction factor scf_e (0.5 year)		0.10
Uncalculated scf_i (flux standard lamps)		0.10
Incident angle dependence correction factor k_b		0.06
Spectral mismatch correction factor ccf_i / ccf_e		0.03
Detector nonlinearity		0.03
Effect of heat by the test lamp (200 W lamp)		0.02
Random noise in the measurement of the external beam	0.03	
Random noise in the measurement of test lamp	0.05	
Reproducibility of test lamp (typical)	0.10	
Overall uncertainty of the luminous flux of test lamps		**0.50**

of total luminous flux based on the illuminance measurement by standard photometers, with no need of flux working standard lamps. An improved accuracy has been achieved as the calibration chain is shortened with the standard lamps and the transfer process eliminated. This method also provides the advantage of automatically correcting the self-absorption of the test lamps and the variation of the sphere responsivity. The process of the periodical realization of the lumen and subsequent recalibration of many working standard lamps are no longer necessary. Instead, the standard photometers and the sphere spatial nonuniformity are calibrated periodically.

In addition, a technique employing a chopper and a lock-in amplifier (the AC/DC technique) for the external source has been introduced, which allows for characterizing the sphere while the internal lamp is burning and for evaluating errors associated with heat and nonlinearities. As a next step, this technique will be implemented as a part of the absolute measurement method.

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